THE REFLECTION OF LIGHT BY GRAVITATION AND THE EINSTEIN THEORY OF RELATIVITY[1]

By SIR JOSEPH THOMPSON,

PRESIDENT OF THE ROYAL SOCIETY IN THE CHAIR.

SIR FRANK DYSON, *The Astronomer Royal:*

The purpose of the expedition was to determine whether any displacement is caused to a ray of light by the gravitational field of the sun, and, if so, the amount of the displacement. Einstein's theory predicted a displacement varying inversely as the distance of the ray from the sun's center, amounting to $1''.75$ for a star seen just grazing the sun. His theory or law of gravitation had already explained the movement of the perihelion of Mercury—long an outstanding problem for dynamical astronomy—and it was desirable to apply a further test to it. Many people considered it quite likely that, even if Einstein's conclusion was not confirmed, we should get half his computed deflection for a beam—this other result being the deflection of a particle moving past the sun with the velocity of light.

The effect of the predicted gravitational bending of the ray of light is to throw the star away from the sun. In measuring the positions of the stars on a photograph to test this displacement, difficulties at once arise about the scale of the photograph. The determination of the scale depends largely upon the outer stars on the plate, while the Einstein effect causes its largest discrepancy on the inner stars nearer the sun, so that it is quite possible to discriminate between the two causes which affect the star's position.

Previous eclipse photographs are generally unsuitable for evidence bearing on the point, as they are either on too large a scale showing too few stars on the plate or else on too small a scale to provide the delicate test with sufficient accuracy. The plates secured at Sfax in 1905 with one of the astrographic objectives used for the International *Carte du Ciel* seemed of suitable scale. Examination of them failed to give a definite result, but showed that this instrument was well suited to our

[1] From the report in *The Observatory,* of the Joint Eclipse Meeting of the Royal Society and the Royal Astronomical Society, November 6, 1919.

problem. A study of the conditions of the 1919 eclipse showed that the sun would be very favorably placed among a group of bright stars—in fact, it would be in the most favorable possible position. A study of the conditions at various points on the path of the eclipse, in which Mr. Hinks helped us, pointed to Sobral, in Brazil, and Principe, an island off the West Coast of Africa, as the most favorable stations, and the eclipse committee decided to send out expeditions to these two places if the war conditions allowed. Professor Turner, of the Oxford University Observatory, most kindly loaned the object-glass of the Oxford astrographic telescope, and the arrangements for mounting this and the Greenwich objective were pushed forward at Greenwich as hard as the reduced staff permitted. Father Cortie further suggested the use of a 4-inch lens of 19 ft. focal length belonging to the Royal Irish Academy. The instruments were assembled at Greenwich largely under Mr. Davidson's supervision, and all was ready in time for the observers to start from England in March.

The Greenwich party, Dr. Crommelin and Mr. Davidson reached Brazil in ample time to prepare for the eclipse, and the usual preliminary focussing by photographing stellar fields was carried out. The day of the eclipse opened cloudy, but cleared later, and the observations were carried out with almost complete success. With the astrographic telescope Mr. Davidson secured 15 out of 18 photographs showing the required stellar images. Totality lasted 6 minutes, and the average exposure of the plates was 5 to 6 seconds. Dr. Crommelin with the other lens had 7 successful plates out of 8. The unsuccessful plates were spoiled for this purpose by clouds, but show the remarkable prominence very well.

When the plates were developed the astrographic images were found to be out of focus. This is attributed to the effect of the sun's heat on the coelostat mirror. The images were fuzzy and quite different from those on the check-plates secured at night before and after the eclipse. Fortunately the mirror which fed the 4-inch lens was not affected, and the star-images secured with this lens were good and similar to those got by the night-plates. The observers stayed on in Brazil until July to secure the field in the night sky at the altitude of the eclipse epoch and under identical instrumental conditions.

The plates were measured at Greenwich immediately after the observers' return. Each plate was measured twice over by Messrs. Davidson and Furner, and I am satisfied that such faults as lie in the results are in the plates themselves and not

in the measures. The figures obtained may be briefly summarized as follows: The astrographic plates gave 0″.97 for the displacement at the limb when the scale-value was determined from the plates themselves, and 1″.40 when the scale-value was assumed from the check-plates. But the much better plates gave for the displacement at the limb 1″.98, Einstein's predicted value being 1″.75. Further, for these plates the agreement between individual stars was all that could be expected. The following table gives the deflections observed compared with those predicted by Einstein's theory:

No. of Star	Displacement in R.A.		Displacement in Dec.	
	Observed	Calculated	Observed	Calculated
	″	″	″	″
11	− 0.19	− 0.22	+ 0.16	+ 0.02
5	− 0.29	− 0.31	− 0.46	− 0.43
4	− 0.11	− 0.10	+ 0.83	+ 0.74
3	− 0.20	− 0.12	+ 1.00	+ 0.87
6	− 0.10	+ 0.04	+ 0.57	+ 0.40
10	− 0.08	+ 0.09	+ 0.35	+ 0.32
2	+ 0.95	+ 0.85	− 0.27	− 0.09

After a careful study of the plates I am prepared to say that there can be no doubt that they confirm Einstein's prediction. A very definite result has been obtained that light is deflected in accordance with Einstein's law of gravitation.

DR. A. C. CROMMELIN, *Assistant Astronomer Royal:*

I have not much to add to what the Astronomer Royal has said, but I should like to say what a great debt we owe to the Brazilian Government for the immense help they gave us. Dr. Morize, the Brazilian national astronomer, gave all possible assistance; he had made a preliminary visit to Sobral a month before, when he made arrangements for our accommodation and also for supplying us with all the labor that we required—porters, bricklayers and carpenters were all freely put at our service. Members of Dr. Morize's staff helped by supplying us with chronometer errors and meteorological data. We were much indebted to Col. Vicente Saboya, the deputy for Sobral, who put his house at our disposal, with a permanent water-supply—no small boon in a time of drought, and of great importance in the photographic work. Dr. Locadio Aranjo, our interpreter, gave us invaluable help at every point, clearly explaining to the workmen our complicated demands, and calling the seconds for us at the eclipse. We were also indebted to the Booth Steamship Company for much help in dealing with our

heavy baggage. They made arrangements with the local companies to forward it free of charge from Para to Camocim and thence to Sobral.

We should also thank the Sobral municipal authorities, who allowed us to encamp on the race-course and kept the public outside during the eclipse.

With regard to the bad focus of the plates taken with the astrographic during totality, we can only ascribe this to a change of curvature of the cœlostat mirror, due to the sun's heat; for the focus was good on the stars two days before the eclipse and again on the check-plates taken during July. The small cœlostat used with the 4-inch lens did not suffer from deformation, the images of stars during totality being of the same character as those on the check-plates; this increased the weight of the determination with that instrument. With regard to the July plates, we found that exposure was possible up to 25 minutes before sunrise, when the sky was of about the same brightness as during totality. $39\frac{1}{2}°$ was the greatest altitude of the field on the check-plates, as compared with 44° at the eclipse.

PROFESSOR A. S. EDDINGTON, *Royal Observatory:*

Mr. Cottingham and I left the other observers at Madeira and arrived at Principe on April 23. We were most kindly received at Principe by Sr. Carneiro. He also supplied us with all the labor and materials we needed, and we established our station at Sundy, the headquarters of his plantation, on the northwest side of the island. The island of Principe is about 10 miles long by 4 miles wide. We soon realized that the prospects of a clear sky at the end of May were not very good. Not even a heavy thunderstorm on the morning of the eclipse, three weeks after the end of the wet season, saved the situation. The sky was completely cloudy at first contact, but about half an hour before totality we began to see glimpses of the sun's crescent through the clouds. We carried out our program exactly as arranged, and the sky must have been a little clearer towards the end of totality. Of the 16 plates taken during the five minutes of totality the first 10 showed no stars at all; of the later plates two showed five stars each, from which a result could be obtained. Comparing them with the check-plates secured at Oxford before we went out, we obtained as the final result from the two plates for the value of the displacement at the limb $1''.6 \pm 0''.3$. The p.e. was determined from the residuals of individual stars. This result supports the figures obtained at Sobral.

There was one important difference in our data—we were unable to stay to take check-photographs of the field. As our eclipse took place in the afternoon, we should have had to wait some months longer than the Sobral observers to get the comparison-plates under the same conditions. We, however, took another field of stars for a check and compared our photographs with the Oxford plates of the same field to see whether a similar reduction gave evidence of any displacement corresponding to that found on the eclipse-plates. We got a very small value for the displacement on these check-plates, leading to the conclusion that the larger quantities found on the eclipse-plates could only be due to the presence of the sun in the field. We also used these check-plates to determine the difference of scale of the photographs at Oxford and Principe, and used that scale for working up the eclipse-plates. This was a great help in making the most of a small amount of material. A difference might have arisen for reasons of temperature changes; but the temperature at Principe is very uniform day and night—in fact, there was not 4° difference during the whole time we were at Principe, and we were there both for the hot and the cold season. Again, in one way we were helped by the clouds that at the time seemed so serious an obstacle; the sun's rays could not seriously affect the mirror by heating it, as seems to have happened at Sobral.

I will pass now to a few words on the meaning of the result. It points to the larger of the two possible values of the deflection. The simplest interpretation of the bending of the ray is to consider it as an effect of the weight of light. We know that momentum is carried along on the path of a beam of light. Gravity in acting creates momentum in a direction different to that of the path of the ray and so causes it to bend. For the half-effect we have to assume that gravity obeys Newton's law; for the full effect which has been obtained we must assume that gravity obeys the new law proposed by Einstein. This is one of the most crucial tests between Newton's law and the proposed new law. Einstein's law had already indicated a perturbation, causing the orbit of Mercury to revolve. That confirms it for relatively small velocities. Going to the limit, where the speed is that of light, the perturbation is increased in such a way as to double the curvature of the path, and this is now confirmed.

This effect may be taken as proving Einstein's *law* rather than his *theory*. It is not affected by the failure to detect the displacement of Fraunhofer lines on the sun. If this latter failure is confirmed it will not affect Einstein's law of gravita-

tion, but it will affect the views on which the law was arrived at. The law is right, though the fundamental ideas underlying it may yet be questioned.

The difference of the two laws may be expressed analytically as follows: Any particle or light-pulse moves so that the integral of ds between two points of its path (in four dimensions) is stationary where

$$ds^2 = -(1-2m/r)^{-1}dr^2 - r^2d\theta^2 + (1-2m/r)dt^2 \text{ (Einstein's law).}$$
$$ds^2 = \qquad -dr^2 - r^2d\theta^2 + (1-2m/r)dt^2 \text{ (Newton's law).}$$

These expressions are in polar coordinates for a particle of gravitational mass m. I think the second expression may be accepted as corresponding to Newton's law—at any rate, it gives no motion of perihelion of Mercury and the half-deflection of light. What we have established is the necessity for the factor multiplying dr^2.

One further point must be touched upon. Are we to attribute the displacement to the gravitational field and not to refracting matter round the sun? The refractive index required to produce the result at a distance of 15′ from the sun would be that given by gases at a pressure of 1/60 to 1/200 of an atmosphere. This is of too great a density considering the depth through which the light would have to pass.

SIR JOSEPH THOMSON, *President of the Royal Society:*

I now call for discussion on this momentous communication. If the results obtained had been only that light was affected by gravitation, it would have been of the greatest importance. Newton did, in fact, suggest this very point in the first query in his "Optics," and his suggestion would presumably have led to the half-value. But this result is not an isolated one; it is part of a whole continent of scientific ideas affecting the most fundamental concepts of physics. It is difficult for the audience to weigh fully the meaning of the figures that have been put before us, but the Astronomer Royal and Professor Eddington have studied the material carefully, and they regard the evidence as decisively in favor of the larger value for the displacement. This is the most important result obtained in connection with the theory of gravitation since Newton's day, and it is fitting that it should be announced at a meeting of the society so closely connected with him.

The difference between the laws of gravitation of Einstein and Newton come only in special cases. The real interest of

Einstein's theory lies not so much in his results as in the method by which he gets them. If his theory is right, it makes us take an entirely new view of gravitation. If it is sustained that Einstein's reasoning holds good—and it has survived two very severe tests in connection with the perihelion of Mercury and the present eclipse—then it is the result of one of the highest achievements of human thought. The weak point in the theory is the great difficulty in expressing it. It would seem that no one can understand the new law of gravitation without a thorough knowledge of the theory of invariants and of the calculus of variations.

One other point of physical interest arises from this discussion. Light is deflected in passing near large bodies of matter. This involves alterations in the electric and magnetic field. This, again, implies the existence of electric and magnetic forces outside matter—forces at present unknown, though some idea of their nature may be got from the results of this expedition.